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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Annual Report for work on "Liquid and Solid Ion Plasmas ONR Contract N00014-89-F0020		5. TYPE OF REPORT & PERIOD COVERED Annual October 1, 1989 - September 31, 1990
7. AUTHOR(s) D.J. Wineland and J.J. Bollinger		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS National Institute of Standards & Technology Div. 576.11 Boulder, CO 80303		8. CONTRACT OR GRANT NUMBER(s) N00014-89-F00020
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Physics Program Office, 800 N. Quincy Arlington, VA 22211		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE 9/15/90
		13. NUMBER OF PAGES
		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public rel ease, distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) nonneutral plasma; one component plasma; strongly-coupled plasma; liquid and solid plasma; plasma distribution functions; Penning trap; laser cooling.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Atomic ions which are stored in electromagnetic fields are an example of nonneutral plasmas. Laser techniques allow control of plasma angular momentum and provide plasma cooling to temperatures much less than 1K. Using imaging techniques, plasma spatial information is achieved. Laser spectroscopic techniques allow measurement of plasma velocity distribution functions. Liquid and solid behavior of ion plasmas is studied.		

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Summary of work on
"LIQUID AND SOLID ION PLASMAS"
(FY '90)

submitted to

Office of Naval Research

ONR Contract No. N00014-89-F0020



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ONR SUMMARY ON "LIQUID AND SOLID ION PLASMAS"

Introduction

In these experiments, performed at the National Institute of Standards and Technology, Boulder, Colorado, atomic ions are stored in combinations of electric and magnetic fields. The resulting nonneutral ion plasmas can be viewed as one component plasmas where global equilibrium is obtained over long times (many hours). The use of atomic ions allows laser cooling, where the temperatures of the plasma can be reduced to 10 mK or less. For the densities typically achieved (up to 10^{10} cm^{-3}) the plasmas become strongly coupled with coupling parameters Γ in excess of 100. The same lasers can be used to impart angular momentum to the plasma which provides a convenient method to control the density. The laser light which is scattered from the ions can also be observed in an imaging camera so the photographs and real time videos of the plasma can be made. Finally, by measuring the spectra of certain transitions in the ions, we can extract Doppler shifts and Doppler broadening which allows us to determine plasma temperature and rotation frequencies (and therefore, densities). Current efforts are devoted to applying these techniques to the measurement plasma dynamics and spatial correlations in ion plasmas.

Accomplishments in FY '90

1. ION PLASMAS NEAR BRILLOUIN LIMIT

We have used radiation pressure from a laser beam to control the rotation frequency ω and obtain ion densities near the Brillouin limit with $\sim 5,000 \text{ } ^9\text{Be}^+$ ions stored in a Penning trap. In addition, rapidly rotating, thermal equilibrium states with $\Omega/2 < \omega < \Omega$ (Ω = cyclotron frequency = 1.4 MHz at $B = 8.2 \text{ kg}$) where the ion density decreases with increasing rotation frequency were also obtained. We have developed a new method to determine ω where the rotation frequency was measured from the spacing of the Doppler-generated frequency-modulation sidebands on the electron spin flip transition ($\sim 22 \text{ GHz}$ at $B = 8.2 \text{ kg}$) in the ground state of $^9\text{Be}^+$. (From the ions' frame of reference, the ion cloud rotation produces an FM modulation of the applied microwaves at the ion cloud rotation frequency ω .)

2. QUADRUPOLE OSCILLATION MODES

In a frame of reference rotating with the ions, the ions behave like a strongly magnetized plasma for rotation frequencies significantly different from $\Omega/2$ but behave like an electrostatically confined plasma near the Brillouin limit ($\omega \sim \Omega/2$). We have been able to observe a smooth transition from strong to weak magnetic field behavior from studies of a quadrupole oscillation mode of the ion plasma. In particular, we have been able to excite and detect an axially symmetric mode where the ion cloud shape always stays spheroidal but changes its aspect ratio by stretching along the trap axis as it shrinks in radius and then shrinks in axial extent as it stretches in radius. For low rotation frequencies ($\omega \ll \Omega/2$) the magnetic field

constrains the radial excursions and the mode turns into an "axial breathing" mode.

The simple spheroidal plasma shapes of a Penning trap plasma have enabled us to analytically calculate this quadrupole mode frequency ω_Q for arbitrary rotation frequency ω . We have experimentally excited this mode by applying a sinusoidal voltage to the ring electrode. When the applied frequency equals the quadrupole mode frequency, the mode is excited and detected by a change in the ion fluorescence due to heating from the excited mode. Agreement between our measurements and calculation is excellent ($\sim 1\%$). Dan Dubin of UCSD has independently calculated this mode and his results agree with our calculation.

We have also observed a heating or increase in the ion plasma temperature at a particular rotation frequency of the ions. This "heating resonance" frequency depended on the trap voltage and was produced by a slight misalignment ($\sim 0.01^\circ$) of the magnetic field axis with the trap symmetry axis. We have theoretically and experimentally determined that this heating resonance is produced by an excitation of an asymmetric tilt mode of the ion cloud. This mode is similar to an $\ell=1$ diocotron mode for a cylindrical plasma column with $\lambda \approx$ axial extent of the plasma. In a frame of reference rotating with the ions, there are two tilt modes which precess in opposite directions. The mode which precesses in the direction opposite to the ion cloud rotation can, at a particular rotation frequency, become a static mode (zero frequency) in the lab frame. This static mode can then be excited by a static asymmetry such as a tilt of the magnetic field. We have measured the rotation frequency of the heating resonance as a function of trap voltage and get very good agreement with our calculation for the static tilt mode.

These modes should have important implications for other experiments. For example, by measuring the symmetric quadrupole frequency ω_Q along with ω_z (axial center of mass frequency) and Ω (cyclotron frequency) information on the cloud shape and rotation frequency is obtained. This should be useful in experiments with electrons, positrons, or antiprotons where laser fluorescence techniques are not applicable and it is otherwise difficult to determine the plasma shape and size. The heating resonance (the asymmetric tilt mode) may set a practical limit on the densities and therefore the number of ions that can be stored in a Penning trap. This would have implications for experiments where storage of a large number of charged particles is important such as in large-scale antiproton storage.

3. NEW PENNING TRAP APPARATUS

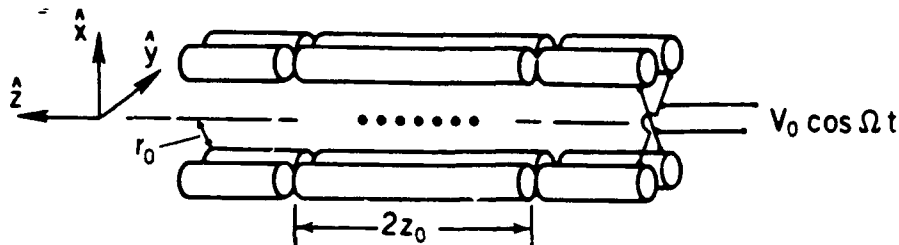
We have been building a new Penning trap apparatus which will provide: (1) the possibility to view the plasmas from the side (in order to see spatial structure along the trap axis), (2) electrodes for exciting asymmetric plasma modes as well as modes with higher than quadrupole ($\ell=2$) order, (3) a more efficient loading system which will help us to avoid the simultaneous storage of unwanted impurity ions, and (4) the possibility of working with larger ion numbers because of the larger trap dimensions. To preserve axial symmetry, the trap electrodes have been machined from a single glass cylinder which will then be coated with graphite to form the electrode surfaces.

The delivery of the superconducting magnet has been delayed by the

manufacturer but it should arrive by mid-summer. The mounting structure for the magnet is already in place so testing can begin immediately upon delivery.

4. LINEAR RF TRAP

We have constructed the rf (ponderomotive) trap which is shown schematically here:



The alternating rf voltage $V_0 \cos \Omega t$ is assumed to be applied to diagonally opposing electrodes as shown. We assume the end portions of the electrodes are long enough that the resulting rf potential at the position of the ions is independent of z , so that the rf electric fields are parallel to the x - y plane. To trap ions along z , we assume the center four electrodes are at static ground potential and the two sets of four electrodes on either end are at a static potential U_0 ($U_0 > 0$ to trap positive ions). The average position of the ions could be made to coincide with the rf electric field null by applying slightly different static potentials to the four central rods to correct for contact potential offsets etc. This geometry would allow laser beams to be directed along the z axis.

This trap was constructed to be able to store large numbers of laser-cooled ions in zero magnetic field. Although "clusters" of small numbers of laser-cooled ions have been observed previously, the storage of large numbers of cooled ions has been precluded because of rf heating. This problem is minimized in the trap shown above. The geometry is similar to that of heavy ion storage rings and therefore should allow us to test some of the predictions about ion crystallization in these devices (for example the formation of helix and shell type structures). Construction has just been completed and tests will begin soon.

5. LASER COOLED REFRIGERATOR

We have theoretically examined a coupled trap experiment where ions (or electrons) in a trap can be cooled by electrically coupling them to ions which are laser-cooled in a second trap. Potentially, such a device could be used to obtain millikelvin temperatures for electron nonneutral plasmas with possible applications to strong coupling studies. A first experiment is being constructed to test the basic scheme. The idea is to cool electrons in one trap by electrically coupling them to ${}^9\text{Be}^+$ ions which are laser cooled in a second trap.

Below are listed all of the research papers (not including abstracts) of the ion storage group at NIST published or submitted since October, 1989. We feel this is appropriate since the work that is not specifically directed toward plasma studies has helped us to develop techniques which are useful in the plasma measurements. The papers which relate directly to plasma studies are denoted by an asterix.

A. PAPERS PUBLISHED IN REFEREED JOURNALS

1. "Test of the Linearity of Quantum Mechanics by rf Spectroscopy of the $^9\text{Be}^+$ Ground State," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert and D. J. Wineland, Phys. Rev. Lett. 63, 1031(1989).
2. "Quantum Zeno Effect," W. M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland, Phys. Rev. A41, 2295 (1990).
- *3. "Microplasmas," J. J. Bollinger and D. J. Wineland, Sci. Am., vol. 262, no. 1, Jan. 1990, p. 124.
- *4. "Quantum-Limited Cooling and Detection of Radio-frequency Oscillations by Laser Cooled Ions," D. J. Heinzen and D. J. Wineland, Phys. Rev. A42, 2977 (1990).

B. PAPERS SUBMITTED TO REFEREED JOURNALS (not yet published)

- *1. "Rotational Equilibrium and Low Order Modes of a Nonneutral Ion Plasma," D. J. Heinzen, J. J. Bollinger, F. L. Moore, W. M. Itano, and D. J. Wineland, submitted.
2. "Progress at NIST towards Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, and M. G. Raizen, IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control; accepted for publication.
3. "Comment on "Nonlinear Magneto-Optics of Vacuum: Second Harmonic Generation"", M. G. Raizen and Baruch Rosenstein, submitted.
4. "A 303-MHz Frequency Standard Based on Trapped Be^+ Ions," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland, IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control; submitted.

C. BOOKS (and sections thereof) PUBLISHED

1. "The Digitized Atom and Optical Pumping," D.J. Wineland, W.M. Itano, J.C. Bergquist and R.G. Hulet, in Atomic Physics 11, ed. by S. Haroche, J.C. Gay, G. Grynberg, (World Scientific Press, Singapore, 1989) p. 741.
- *2. "Liquid and Solid Phases of Laser Cooled Ions," S.L. Gilbert, J.C. Bergquist, J.J. Bollinger, W. M. Itano, and D.J. Wineland, in Atomic Physics 11, ed. by S. Haroche, J. C. Gay, and G. Grynberg (World Scientific Press, Singapore, 1989) p. 261.
3. "Progress at NIST Towards Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, and C. S. Weimer, proc. 43rd Annual Symposium on Frequency Control, Denver, June, 1989, IEEE Catalog no. 89CH2690-6.
- *4. "Observation of Correlations in Finite, Strongly Coupled Ion Plasmas," J. J. Bollinger, S. L. Gilbert, D. J. Heinzen, W. M. Itano, and D. J. Wineland, in Strongly Coupled Plasma Physics, ed. by S. Ichimaru, (Elsevier Science Publishers B.V. / Yamada Science Foundation, 1990) p. 177.
5. "Hg⁺ Single Ion Spectroscopy," J. C. Bergquist, F. Diedrich, W. M. Itano, and D. J. Wineland, in Laser Spectroscopy IX, ed. by M. S. Feld, J. E. Thomas, and A. Mooradian (Academic, San Diego, 1989), p. 274.
- *6. "Laser Cooling and the Formation of Coulomb Crystals," J. C. Bergquist, 1991 Yearbook of Science and Technology, McGraw Hill Publishing Co.
- *7. "Liquid and Solid Plasmas," J. J. Bollinger, S. L. Gilbert, D. J. Heinzen, W. M. Itano, and D. J. Wineland, in Atomic Processes in Plasmas, ed. by Y. K. Kim and R. C. Elton, AIP Conference Proceedings 206, (American Institute of Physics, New York, 1990) p. 152.

D. BOOKS (and sections thereof) SUBMITTED

1. "Quantum Optics of Single, Trapped Ions," W. M. Itano, J. C. Bergquist, F. Diedrich, and D. J. Wineland, proc. Sixth Rochester Conference on Coherence and Quantum Optics, Rochester, N. Y., June, 1989, to be published
2. "Test of the Linearity of Quantum Mechanics by RF Spectroscopy of the $^9\text{Be}^+$ ground State," D. J. Heinzen, J. J. Bollinger, W. M. Itano, S. L. Gilbert, and D. J. Wineland, *ibid.*
- *3. "Cooling Methods in Ion Traps," W. M. Itano, J. C. Bergquist, J. J. Bollinger, and D. J. Wineland, chapter in Physics with Charged Particles in a Trap, edited by G. Gabrielse and G. Werth, submitted.
- *4. "Trapped Atoms and Laser Cooling," D. J. Wineland, "essay" for undergraduate text Physics, by Paul Tipler, submitted.
5. "Progress at NIST on Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, M. G. Raizen, and C. S. Weimer, proc. 4th European Frequency and Time Forum, Neuchatel, March 1990, to be published.
6. "Atomic Physics Tests of Nonlinear Quantum Mechanics," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland, in Atomic Physics 12, proc. 12th Int. Conf. on Atomic Physics, ed. by R. Lewis and J. Zorn, A. I. P. Conference proceedings, to be published.

E. INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. Seventh APS Topical Conference on Atomic Processes in Plasmas, Gaithersburg, Md., October, 1989, D. J. Wineland.
2. Optical Society of America, Annual Meeting, Orlando, Fla., October, 1989, W. M. Itano.
3. Winter College on High Resolution Spectroscopy, International Centre for Theoretical Physics, Trieste, Italy, January, 1990, W. M. Itano.
4. European Forum on Time and Frequency, Neuchatel, Switzerland, March, 1990, D. J. Wineland.
5. Precise Frequency Measurements Meeting, Communications Research Laboratory, Tokyo, Japan, March 1990, W. M. Itano.
6. Ninth International Laser Spectroscopy Conference, Bretton Woods, New Hampshire, June, 1989, J. C. Bergquist.
7. Gordon Conference on Atomic Physics, Wolfboro, New Hampshire, July, 1989, J. C. Bergquist.
8. Spring Meeting of APS, Washington, D. C., April, 1990, D. J. Wineland.
9. Meeting on "Light Induced Kinetic Effects on Atoms, Ions and Molecules," Pisa, Italy, May, 1990, J. C. Bergquist.
10. APS Division on Atomic, Molecular, and Optical Physics (DAMOP), Annual Meeting, Monterey, Ca., May, 1990, J. C. Bergquist and D. J. Wineland.
11. Workshop on the foundations of Quantum Mechanics, Santa Fe, N. M., May 1990, D. J. Heinzen.
12. Conference on Precision Electromagnetic Measurements, Ottawa, Canada, June, 1990, W. M. Itano.
13. International Conference on Atomic Physics (ICAP), Ann Arbor, Michigan, July, 1990, J. J. Bollinger.
14. Gordon Conference on Few Body Systems, Proctor Academy, N. H., Aug. 1990, D. J. Wineland.
15. U. S./ Japan Seminar on "Quantum Electronic Manipulation of Atoms and Fields," Kyoto, September, 1990, D. J. Wineland.

F. OTHER INVITED TALKS (Colloquia etc.)

1. Univ. of Notre Dame, Notre Dame, Ind. September, 1989, J. J. Bollinger.
2. Laval University, Quebec, Canada, October, 1989, D. J. Wineland.
3. Rochester Univ., Rochester, N. Y., November, 1989, D. J. Heinzen.
4. Univ. of Oregon, Eugene, Oregon, November, 1989, D. J. Wineland.
5. Cal Tech, Pasadena, Ca., November, 1989, D. J. Wineland.
6. Washington Univ., St. Louis, Mo., December, 1989, W. M. Itano.
7. National Physical Laboratory, Teddington, England, December, 1989, D. J. Wineland.
8. Univ. of Wisconsin, Madison, Wisconsin, January, 1990, D. J. Heinzen.
9. M I T, Cambridge, Mass., February, 1990, D. J. Heinzen.
10. Lawrence Berkeley Laboratory, Berkeley, Ca., February, 1990, W. M. Itano.
11. Stanford Linear Accelerator, Stanford, Ca., February, 1990, W. M. Itano.
12. Univ. of Calif., San Diego, La Jolla, Ca., February, 1990, D. J. Wineland.
13. Ecole Normale, Paris, France, March, 1990, D. J. Wineland.
14. General Electric, Schenectady, N. Y., March, 1990, J. J. Bollinger.
15. Tokyo Institute of Technology, Yokohama Japan, April, 1990, W. M. Itano.

16. Okayama Univ., Okayama, Japan, April, 1990, W. M. Itano.
17. University of Electrocommunications, Tokyo, Japan, April, 1990, W. M. Itano.
18. Univ. of Tokyo, Tokyo, Japan, April, 1990, W. M. Itano.
19. Univ. of Chicago, Chicago, Ill., April, 1990, J. J. Bollinger.
20. IBM Almaden Research Center, San Jose, Ca., May, 1990, D. J. Wineland.
21. Rice University, Houston, Texas, January, 1990, J. J. Bollinger.
22. UCLA, Los Angeles, January, 1990, D. J. Heinzen.
23. Univ. of Washington, Seattle, September, 1990, D. J. Heinzen.
24. George Washington / NSF colloquium, September, 1990, D. J. Wineland.

G. HONORS/AWARDS/PRIZES

1. Election to Fellow of the American Physical Society, J. C. Bergquist.
2. 1989 Samuel Wesley Stratton Award (NIST), for ion frequency standard development. Shared by J. C. Bergquist, J. J. Bollinger, W. M. Itano, and D. J. Wineland.
3. 1990 Davisson-Germer Prize (APS), D. J. Wineland.